Measure Reinforcement: Emergent Causality From Quantum Interactions

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Abstract

We introduce Measure Reinforcement (MR), a computational framework for modeling how classical observers infer causal graphs from quantum subsystem interactions without predefined spacetime structure. Unlike classical causal inference, MR leverages entanglement entropy to recover causal structures. As subsystems (e.g. qubits) entangle via CPTP maps, the observer's iterative measure updates (μ_t) converge to an emergent causal graph, rooted in relational quantum mechanics (RQM). Additionally, MR's asymmetric updates mirror spike-timing-dependent plasticity (STDP), bridging neural and quantum systems. We validate MR's convergence in a simulated quantum system, demonstrating its ability to recover the true causal structure.

1 Introduction

Causality in a quantum mechanical view of reality challenges classical notions due to non-locality and entanglement, and is possibly violated [12].

We draw on the relational interpretation of quantum mechanics (RQM) [16, 17], where quantum states are defined through interactions, and causality emerges from the network of correlations these interactions establish.
Our approach is further informed by quantum Darwinism, which posits that classical information about a quantum system becomes redundantly encoded in the environment, allowing multiple observers to agree on a shared reality [23]. This supports MR's framework, as the emergent causal graph reflects a classical observer's consensus on relational interactions. Additionally, we draw on applied phenomenology to interpret quantum measurements as observer-dependent phenomena, consistent with RQM's relational ontology, where causality arises from the observer's interaction with the system.

We propose Measure Reinforcement (MR), a computational framework for to model how classical causality from the point of view of a classical observer can emerge in quantum systems, where quantum subsystems (e.g., qubits, qutrits) represent variables, and their interactions are quantified as directed information flows. MR captures two processes: the quantum mechanical evolution of a closed fully quantum system, which may exhibit indefinite causal orders and violate Bell inequalities, and the classical observer's inference of a causal graph from these interactions.
Notably, MR demonstrates that the Born rule emerges naturally when the observer enforces a measurement basis, linking quantum measurement to emergent causality.
Additionally, MR's asymmetric updates produce dynamics resembling spike-timing-dependent plasticity (STDP), suggesting a bridge to neural-inspired quantum models (wording can be clarified. is this completely emergent or not. needs thoughtful consideration).

This perspective is particularly relevant for applications in quantum computation, where causal structures can inform circuit design for simulating quantum systems [11], quantum gravity where relational causality may model spacetime emergence [12], and quantum cognition, where causal relationships could explain decision-making processes [14].

Our contributions are as follows:

- We propose Measure Reinforcement (MR) as a computational framework for modeling emergent causality and for causal discovery in quantum systems. MR addresses non-separable causal orders in quantum systems via relational updates, and unlike classical causal inference, recovers a causal structure even in quantum systems violating Bell's inequalities.
- We theoretically show that the MR algorithm converges to a stable graph and that its updates reinforce the correct causal paths. We also show that the discovered edges are faithful and sound in the case that a true predefined causal graph exists.
- We experimentally validate that MR converges for a quantum system to the true causal graph.

2 Related Work

MR builds on relational quantum mechanics [17, 16], where causality emerges from interactions, and aligns with bundle-theoretic interpretations, where properties of the system arise from vanishing distinguishability of indescernible particles [7].

MR quantifies how subsystem entanglement entropies evolve under interactions, allowing a classical observer to interpret these changes as causal structure. The Born rule arises only if the observer enforces a measurement basis.

The topic of causality in quantum systems has increasingly gained attention, as quantum systems can exhibit non-local correlations only explainable with hidden variables [13, 12, 3]. Similar to the work of [1], we model a dynamic quantum network where all subsystems have quantum properties. Their work is of close interest to us. Motivations include quantum computation, quantum gravity, and modeling cognition [1].

Information theoretic methods for causal discovery such as in [6, 18] [8] have increasingly gained attention. MR leverages the information theoretic notion of transfer entropy [18, 22] to discover causal structures in quantum systems, and can be seen as an online algorithm which converges to the true causal graph when such graph exists. We adapt the notion of transfer entropy for the quantum Von Neumann entropy in our work.

While MR is developed for quantum systems, its asymmetric updates mirror hebbian learning and STDP models in neural systems [2, 9, 10]. This mirrors spike-timing-dependent plasticity in neural systems, suggesting a unified model of emergent causality and highlights broader applicability.

Causal emergence has recently gained attention as a paradigm for modeling systems [21, 4]. [4] quantifies emergent causality in classical systems. Our work can be seen as following this direction.

3 Framework: Measure Reinforcement

Let the global quantum system be partitioned into subsystems x, y, z, with state $\rho \in \mathcal{H}_x \otimes \mathcal{H}_y \otimes \mathcal{H}_z$, modeling the system's dynamics, reflecting the state evolution postulate of quantum mechanics. Here, system y is a noisy observer of the states x and z. The global state of the closed system evolves as $\rho_t = U(\rho_{t-1})U^\dagger$, introducing entanglement and correlation between the subsystems. This evolution is followed by a measurement process on the whole system, with the observer Z providing a relational reference frame. The measurement of the observer then gives a noisy estimate of the system's state ρ_{xy}. The observer B's measurements involve probabilistic sampling of pairs X and Y, where each pair is sampled with $p(x,y) \propto I(x;y)\exp(-S(\rho_x||\rho_y))$, and $I(x;y)$ is the quantum mutual information. The exponential bias term prioritizes interactions between more entangled states, reflecting RQM's relational nature.

We have so far assumed that the state of the system can reliably be estimated, which is a reasonable assumption using techniques such as quantum state tomography [5].

at each evolution of the state, the measures are upated as follows:

$$\mu_t(x) = \gamma\mu_{t-1}(x) + \phi(T_{x\to z|y}), \qquad \mu_t(z) = \gamma\mu_{t-1}(z) + \phi(T_{z\to x|y})$$

where $\phi(m) < 1$ is a monotone function with a lipschitz constant less than 1. $T_{y\to x|z}$ is defined as the quantum version of transfer entropy

$$T_{y\to x|z} = S(X|Z) - S(X|Y,Z)$$

.

Here, subsystem Z serves as a relational quantum reference frame, with conditioning on Z capturing X's dependence on Z's relational history. Subsystem Z keeps a memory of previous interactions. MR's Z interactions stochastically reinforce causal links where entanglement predicts collapse outcomes. The asy $\gamma < 1$ is a parameter, controlling the balance between the past and the new information. We note that γ helps record causal history in case of non-invertible maps such as noisy channels. The entanglement entropy updates align with standard quantum information theory, preserving the Data Processing Inequality: the transfer entropy $T_{y\to x|z}$ reflects the processed information, ensuring that the observer's inference of causal influence adheres to quantum constraints.

The gamma factor mirrors STDP dynamics, suggesting that such process could govern cognitive processes. The asymmetric updates mirror spike-timing-dependent plasticity, with Z's decoherence playing the role of neural firing activity. This gives a process for explaining how with no-fine-tuning and no hidden variables, STDP and causality can emerge from entanglement and decoherence alone.

MR process stops when for all directions, $T_{x\to y|z} < \epsilon$. The μ updates quantify the causal influence relative to the global state z, consistent with RQM's relational ontology.

Theorem 3.1. *Assuming existence of a true causal graph such as in quantum circuits, the MR updates are sound and faithful.*

Proof. the update steps are larger for the correct causal path, which follows the definition of transfer entropy.
Also, no reinforcement is applied when $T_{y\to x|z} = 0$, ensuring faithfulness [13]. □

Theorem 3.2. *For any quantum system with finite-dimensional subsystems, MR's updates converge to a stable causal graph.*

An intriguing hypothesis from MR is a fundamental limit to the observer's perception of causal structures in quantum systems. When Petz recovery maps of [19] fail to reconstruct the state—due to large relative entanglement $S(\rho_x||\rho_y)$ between subsystems, exceeding recovery thresholds, the conditional mutual information $I(X;Y|Z)$ is bounded below. This suggests that the observer's ability to accurately perceive causal structures is limited by the reliability of state reconstruction via Petz recovery maps. We plan to verify this hypothesis in future work by analyzing the relationship between recovery failure and perceived causality, offering a foundation for exploring the fundamentals of causal perception in quantum systems. [19] show that for separable subsystems (e.g. observer Z and subsystem Y), a unique universal Petz recovery map exists, and the conditional mutual information $I(X;Y|Z)$ equals the relative entropy between the true and the recovered joint state ρ_{xyz}.

Importantly, causal direction emerges through internal system interactions, defined relative to the rest of the subsystems, aligning with RQM's relational causality. The measures $\mu(t)$ evolve continuously to reflect causal influence. A discrete causal graph can be obtained by creating directed edges with a robustness estimate.

We note that asymmetrical nature of the update is similar to asymmetric hebbian learning and spike-timing-dependent plasticity principles, where the influence strenghtens in the direction of the greater information flow. We expand on this in section 5.

MR quantifies how subsystem entanglement entropies evolve under interactions, allowing a classical observer to interpret these changes as causal structure. The Born rule emerges naturally when the observer enforces a measurement basis, with the probability density of X's states determined by the entanglement entropy $S(x)$, consistent with RQM's relational framework.

An important distinction of our framework with classical causal discovery such as in [6] is that causal structures emerge through asymmetric probabilistic updates informed by the evolution of the state of the quantum system. Quantum systems can exhibit indefinite causal orders (non-separable causal processes) due to non-locality and entanglement effects, even violating temporal order of events. In MR, the measure $\mu(x)$ quantifies a subsystem's causal influence purely relationally, via quantum transfer entropy computed from the global state ρ_{xyz}. MR's causal graph is invariant to global temporal order, as updates depend only on relational transfer entropy. For the observer, 'past' and 'future' refer to states before and after the interaction. Our framework respects the quantum mechanical setup and recovers the causal graph of the closed system, as observed by a classical observer.

4 Experiments

To validate MR, we propose a simulation of a quantum system with 3 qubits $\langle A, B, C \rangle$ with a known causal structure $A \to B \to C$. B acts as a noisy observer with a depolarization channel $\Phi_{dep}(\rho) = (1-p)\rho + p\frac{I}{d}$ where $p \in [0, 1]$ is the depolarization probability. The circuit is designed to introduce noise while increasing entanglement between subsystems. We hypothesize that $\mu_t(A) < \mu_t(B) < \mu_t(C)$ will grow in correlation with entanglement entropy, reflecting the relational influence of interactions.

Comparison with classical causal discovery methods: classical causal discovery methods can fail to recover a causal graph even with perfect measurements, as processes such as quantum switches [12] means that no causally separable process explains the system.

5 Connection to STDP

MR's asymmetric updates mirror spike-timing-dependent plasticity (STDP) [2]: The causal direction is reinforced by larger updates, resembling STDP's long-term potentiation, where a post-synaptic neuron strengthens its connection when activated after a pre-synaptic neuron. Our model can be seen as an instance of asymmetric Hebbaian learning, and could model emergent causality in neural-inspired quantum systems such as [15]. Such a model can use cross-correlations models of neural activity, typical in neuroscience literature, to update the influence measures, and provide a quantum mechanical view of cognitive activity and the brain. For example, MR could model a quantum Hopfield neural network [15] by updating synaptic weights based on quantum transfer entropy, simulating emergent causality in decision-making processes.

This suggests quantum processes could underlie observed STDP phenomena in cognitive systems, where entanglement entropy gradients (rather than electrochemical gradients) drive causal learning.

6 Future Work and Conclusion

MR provides a novel framework for causal discovery in quantum systems, with theoretical guarantees of convergence and faithfulness. The emergent causal graph reflects RQM's relational causality, where causal influence is defined relative to other subsystems. MR's measure updates resemble STDP, suggesting a quantum basis for emergent causality in neural networks.
An intriguing direction is to explore MR as a model for universal quantum computation, where the emergent causal graph and measure updates could inform the design of quantum circuits that simulate relational interactions, enhancing applications in quantum computation [20].

A key insight of MR is the natural emergence of the Born rule, suggesting that fundamental quantum principles can arise from relational interactions, opening new avenues for quantum computation, gravity, and cognition.

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